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## Substrate-dependent quasiparticle recombination time in superconducting resonators

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# Substrate-dependent quasiparticle recombination time in superconducting resonators

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We demonstrate an increased quasiparticle recombination time in superconducting resonators on a SiN<sub>x</sub> membrane, compared to identical resonators on a SiN<sub>x</sub>/Si wafer. An interpretation is given using a thermal model of the membrane. Using an array of tunnel junctions to cool or heat the membrane, we show that the resonators on the membranes are extremely sensitive to small changes of the phonon temperature, which renders them excellent phonon thermometers with a noise level equivalent to  $5\mu\text{K}/\sqrt{\text{Hz}}$ . The experimental set-up is in principle an ideal platform to study the interplay of quasiparticles and phonon populations in superconductors. © 2011 American Institute of Physics. [doi:10.1063/1.3624463]

Superconducting devices for space astronomy and quantum computation are operated at temperatures below 300 mK. At those low temperatures, it is usually assumed that the electronic system of the superconductor reaches the temperature of the environment, leading to a low density of quasiparticles – low enough to minimize loss and the recombination rate and to maximize the coherence time in qubits. In practice, it has been found that the quasiparticle density is higher than what can be expected based on the temperature alone.<sup>1</sup> In addition, in many experiments, the recombination rate is influenced by the interaction with the phonons, as has been analyzed early in the context of laser-pulse experiments by Rothwarf and Taylor.<sup>2</sup> We report on the development of a platform to study the interplay between phonons and electrons, which enables a comparison of resonators on different support structures as well as a possibility to add phonons (heating) or remove phonons (cooling) from the material interacting with the resonator.

A SiN<sub>x</sub> membrane<sup>3</sup> of thickness 100 nm and macroscopic area of  $1 \times 1 \text{ mm}^2$  is equipped with two Al quarterwave superconducting resonators (light square in Fig. 1(a) with resonators, schematic cross section in Fig. 1(c)). Four resonators are located on the full SiN<sub>x</sub>/Si wafer, consisting of 100 nm SiN<sub>x</sub> on 200  $\mu\text{m}$  Si. The resonators are patterned by electron beam lithography (EBL) and a chlorine reactive ion etch, after sputter deposition of a 100 nm thick Al film.

The samples are measured in a He-3 sorption fridge with a base temperature of 300 mK. Measurements on all six resonators are performed simultaneously with a single feed line, to which the resonators are capacitively coupled. The transmission  $S_{21}$  is measured with a signal generator, a low noise cold amplifier, a quadrature mixer, and an analog to digital converter.<sup>4</sup> Through the kinetic inductance of the superconducting condensate, the resonant frequency  $f_0$  of each resona-

tor depends on the Cooper pair density and hence on variations in the number of quasiparticles  $\delta n_{qp}$ , ( $kT \ll \Delta$ ),

$$\frac{\delta f}{f_0} = -\frac{\alpha\beta}{4} \frac{1}{\pi 2N_0 \sqrt{\hbar f \Delta/2}} \delta n_{qp} = R \delta n_{qp}, \quad (1)$$

where  $\alpha$  is the ratio of the kinetic inductance to the total inductance,  $\beta$  is a geometric factor characteristic for the superconducting surface resistance,  $\Delta$  is the superconducting gap, and  $R$  is the responsivity.<sup>4</sup> The phase  $\theta$  of  $S_{21}$  is a direct measure for the number of quasiparticles through the relation  $\delta\theta = -4Q_L \frac{\delta f}{f_0} = -4Q_L R \delta n_{qp}$ , with  $Q_L$  the loaded quality factor.

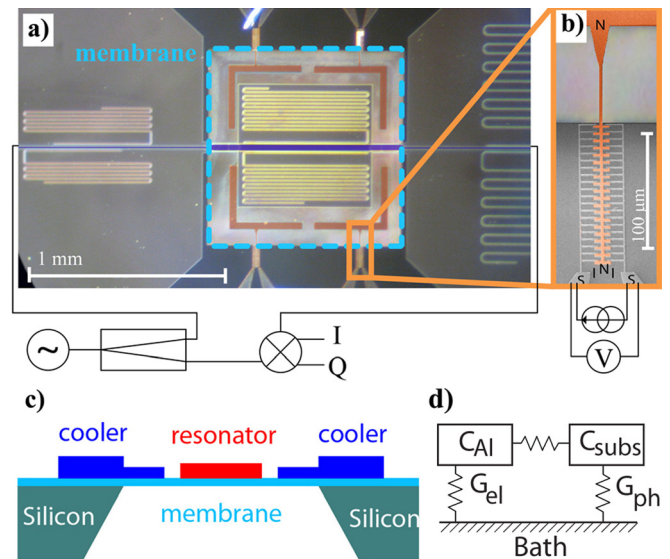


FIG. 1. (Color online) (a) Six Al superconducting resonators, of which four are located on the SiN<sub>x</sub>/Si wafer and two on a 100 nm thick,  $1 \times 1 \text{ mm}^2$  SiN<sub>x</sub> membrane. Four L shaped Cu slabs thermalize the membrane to four junction arrays, each consisting out of 20 SINIS tunnel junctions (b). (c) Schematic cross section of the device layout. (d) Thermal circuit diagram,  $C_{Al}$  and  $C_{subs}$  are the respective heat capacities of the Al film and the substrate.  $G_{el}$  and  $G_{ph}$  are the electronic and phononic heat conductances.

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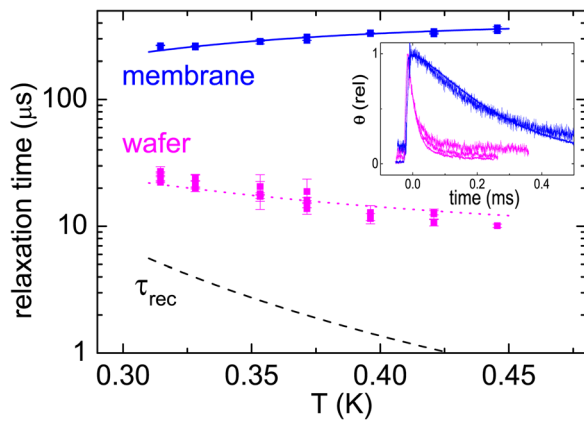


FIG. 2. (Color online) Relaxation times of resonators on the membrane and on the SiN<sub>x</sub>/Si wafer, the full and dotted lines correspond to a thermal model. The dashed line shows  $\tau_{rec}$  after Ref. 7 with  $\tau_0 = 480$  ns. The relaxation of the resonators after an optical pulse is seen in the real time phase response of the resonators, at a bath temperature of 315 mK (inset).

The inset of Fig. 2 shows the real time phase response of the different resonators after optical excitation with a 1.9 eV GaAsP light emitting diode (LED). For small excitations, the response is linear and can be characterized by a single exponential decay time  $\tau_R$ . As shown in the figure, the values of  $\tau_R$  are an order of magnitude higher for the resonators on the membrane than for the ones on the SiN<sub>x</sub>/Si wafer. In addition, their dependence on temperature is strikingly different. The relaxation time of the resonators on the membranes increases with increasing temperature, where the resonators on the SiN<sub>x</sub>/Si show the opposite temperature dependence.

In previous works,<sup>5,6</sup> relaxation times have been successfully explained in terms of quasiparticle recombination, which predicts a rate proportional to the quasiparticle density and which decreases exponentially at low temperatures,<sup>7</sup>

$$\tau_{rec} = \frac{\tau_0}{\sqrt{\pi}} \left( \frac{kT}{2\Delta} \right)^{5/2} \sqrt{\frac{T_c}{T}} \exp(\Delta/kT). \quad (2)$$

The data on the wafer show a similar tendency, although for a typical scattering time for Al of 480 ns (dashed line Fig. 2), the observed times are too long and decay much more slowly with temperature. In this temperature range, a similar deviation has been reported recently by De Visser *et al.*,<sup>1</sup> who found a discrepancy between relaxation times inferred from generation-recombination noise measurements and those obtained with the technique used here. Furthermore, Barends *et al.* found<sup>5</sup> a similarly strong difference between Al resonators on silicon or on sapphire. It suggests that in using the LED technique at these temperatures, the measured  $\tau_R$  is influenced by the substrate phonons.

For the resonators on the membrane, the magnitude as well as the temperature dependence make it unlikely that the relaxation is limited by quasiparticle recombination. Enhanced relaxation times can be attributed to reabsorption of  $2\Delta$ -phonons emitted during recombination, as described by Rothwarf and Taylor.<sup>2</sup> If the time  $\tau_{esc}$  for a phonon to escape from the superconducting film exceeds the time  $\tau_{pb}$  to break a Cooper pair, the quasiparticle recombination time becomes longer and given by  $\tau_R = \tau_{rec}(1 + \tau_{pb}/\tau_{esc})$ . As  $\tau_{esc}$  and  $\tau_{pb}$  are only weakly temperature dependent, the expo-

nential increase of  $\tau_R$  at low temperatures is preserved. To understand the observed opposite temperature dependence, we propose a thermal description of the resonator and the membrane, qualitatively sketched in Fig. 1(d). The theoretically expected recombination time is much shorter than the relaxation times measured. Therefore, we assume that the phonons in the membrane and the quasiparticles in the resonator are each in equilibrium at their respective temperatures. The relaxation time of the system, membrane, and resonators thermally coupled to the support structure is then given by the ratio of the total thermal capacitance to the thermal conductance,  $\tau_R = \frac{C_{th}}{G_{th}}$ .

The heat capacity  $C_{th}$  is dominated by the electronic capacity  $C_{Al}$  of the Al film, taken from Phillips,<sup>8</sup> which is at the given temperatures three orders of magnitude larger than the one of the Al and SiN<sub>x</sub> crystal-lattices. Relaxation happens through two parallel channels: the electronic conductance  $G_{el}$  of the Al feed line and the phononic conductance  $G_{ph}$  of the membrane. Given the total cross section  $S = 8 \mu\text{m}^2$ , length  $L = 150 \mu\text{m}$ , and diffusion constant  $D$  of the feed line, we define  $G_{el} = DC_{Al}S/A$ . To facilitate the calculation of the thermal conductance of the membrane, we assume a circular geometry. We find  $G_{ph} = \frac{2\pi d}{\ln(r)} \kappa_m$ , with  $r = 1.35$ , the ratio of the membrane radius to the part covered with Al. The heat conductance  $\kappa_m = 4T^{2.1} \text{ mW/K}^2$  was measured from a similar membrane with the techniques described by Leivo and Pekola.<sup>9</sup> The result is given by  $\tau_R = \frac{C_{Al}}{G_{el} + G_{ph}}$  and shown as a full line in Fig. 2. The only adjustable parameter is the diffusivity  $D = 130 \text{ cm}^2/\text{s}$ , in agreement with resistivity measurements of comparable films. Despite the simplicity of the model, the correct magnitude and temperature dependence of  $\tau_R$  is retrieved, implying that the thermal response of the membrane is the limiting factor in the measurements shown in Fig. 2.

We apply an analogous, thermal analysis to the relaxation times measured on the wafer. The heat capacity of the P-doped Si wafer consists of an electronic and a lattice component,<sup>10</sup> and dominates over the electronic heat capacity of the Al film, as the wafer is much thicker. Relaxation occurs through the quasiparticles of the Al bondwires and by phonons escaping through the interface between the wafer and the (cold) sample holder. The electronic contribution  $G_{el}$  of the bondwires is modeled as above, for the phononic contribution  $G_{ph}$  a Kapitza resistance is used. The resulting relaxation times  $\tau_R = \frac{C_{Al} + C_{Si}}{G_{el} + G_{ph}}$  (dotted line in Fig. 2) show the thermal model is consistent with the measured data.

The above discussion indicates that the phonons of the substrate play a role in the quasiparticle relaxation time of superconducting resonators, both on the membrane as on the SiN<sub>x</sub>/Si wafer, though in different strengths. A distinction will have to be made between nonequilibrium phonons in the superconductor itself and phonons in the substrate. In a preliminary attempt, we have included in the design the possibility to raise or lower the temperature of the membrane phonons, using an array of superconductor-insulator-normal metal-insulator-superconductor (SINIS) tunnel junctions.<sup>11</sup> We demonstrate that the response of the resonators is very sensitive to heating and cooling of the phonons.

Four arrays of 20 Al/AIO<sub>x</sub>/Cu/AIO<sub>x</sub>/Al SINIS tunnel junctions each (Fig. 1(b)) are deposited using shadow



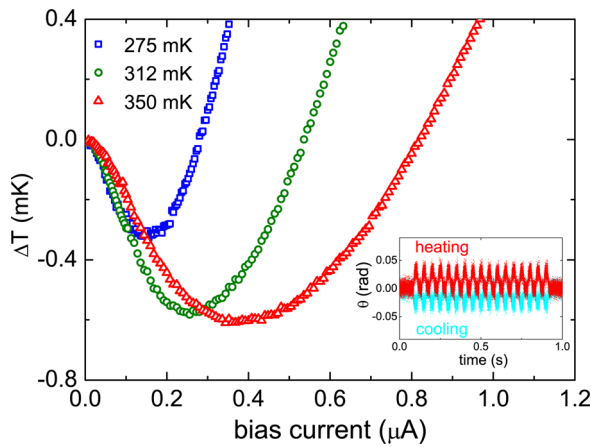


FIG. 3. (Color online) The temperature difference of the superconducting resonator versus the bias currents of the junction array, at three different bath temperatures. The inset shows the real time phase response  $\theta$  of the resonator to two different biases, modulated with a 20 Hz square wave.

evaporation through a double resist layer, patterned by EBL. A 20 nm thick Al layer is oxidized *in situ* for 5 min in a pure oxygen atmosphere at a pressure of 4.6 mbar to create the tunnel barrier and covered with a 50 nm Cu top layer. Four massive L-shaped Cu slabs are located on the membrane (Figs. 1(a) and 1(b)) to thermalize the membrane phonons to electrons of the junction.

Using a battery-powered current bias, we measure the current voltage characteristic (IV) of the junction array. Due to fast electron-electron interactions, the Cu electrons are assumed to be in quasi-equilibrium with a temperature  $T_N$ . The current is then given by

$$2eR_n I = \int dE N(E) [f_N(E + eV/2, T_N) - f_N(E - eV/2, T_N)], \quad (3)$$

where  $R_n$  is the normal state resistance,  $f_N$  is the superconducting density of states, and  $f_N$  is the occupation number of the normal metal electrons. Due to the superconducting gap, only electrons with an energy higher than  $E > \Delta - eV/2$  can tunnel out of the normal metal. At low voltages  $eV < 2\Delta$ , this results in cooling of the normal metal electrons. At higher voltages, pair breaking becomes possible with heating as a result. The temperature  $T_N$  can be obtained from the measured IV using Eq. (3), with  $R_n = 18.3 \Omega$  and  $\Delta = 205 \mu\text{eV}$ .

Fig. 3 shows the temperature of the resonator on the membrane as a function of the bias current applied to the junctions, at three different bath temperatures. Cooling and heating of the resonator are clearly observed, with a maximum cooling of 0.6 mK (corresponding to 10 mK at the junction, at a voltage  $V \approx 0.25$  mV (Ref. 12)). The fact that

we observe quasiparticle cooling of the resonators indicates that the membrane phonons mediate the cooling of the junction.

The temperature of the resonator is inferred from the phase response (inset Fig. 3), using  $\delta\theta = -4QJR\delta n_{qp}$  and  $n_{qp} = 2N^a(0)\sqrt{2\pi kT\Delta}e^{-\Delta/kT}$ . The high quality factors  $Q_I \approx 10^4 - 10^6$  make these resonators extremely sensitive, as can be seen from the accuracy with which temperature differences smaller than a mK can be measured. To quantify this, we calculate which temperature difference generates a signal equal to the system noise:  $S_{\Delta T} = S_{\text{Noise}}$ . For phase read out, this is equivalent to  $\frac{d\theta}{dT}\Delta T = \Delta\theta_{\text{Noise}}$ . At an integration time of 1 s, this gives an equivalent temperature difference of  $\Delta T < 5 \mu\text{K}$ . This demonstrates the potential of resonators as sensitive thermometers, suitable for time resolved measurements, analogous to recent results for detection of phonons generated by cosmic rays.<sup>13</sup>

In conclusion, we experimentally studied the interplay between phonon and quasiparticle nonequilibrium in a superconducting resonator. We have demonstrated that the relaxation times of resonators on a  $\text{SiN}_x$  membrane are an order of magnitude higher than the ones on the  $\text{SiN}_x/\text{Si}$  wafer. We have also shown that the response of the resonators is very sensitive to the phonon bath of the membrane, of which we electronically changed the temperature. Ideally, it should also be possible to include SIS tunnel junctions to generate not just a thermal phonon distribution but also preferentially  $2\Delta$ -phonons from recombination.<sup>14</sup>

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